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Exergy analysis of cascaded encapsulated phase change material—High-temperature thermal energy storage systems

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ABSTRACT

The second law analysis of an example thermal energy storage (TES) system was conducted to determine the benefit of a system employing a multiple phase change materials. Six systems were considered: three single PCM systems ($NaNO_3$, $NaNO_2$, and KNO_3), a 2-PCM system a 3-PCM system, and a sensible heat only system as a comparison. The latent heat-based systems were able to store more energy and exergy with comparable efficiencies than a system that relies on sensible heat only. Furthermore, when the overall cyclic performance was examined and showed that systems with multiple PCMs outperform their corresponding single PCM-based systems. While for the operating conditions and PCMs chosen the 2-PCM system (NaNO3/NaNO2) was superior, great care is required during the design of an EPCM-based TES system as the difference between the melting point of the PCMs and the inlet temperatures during charging and discharging greatly affect the performance of the system.

1. Introduction

The limited supply of fossil fuels in the world coupled with ongoing concerns over the environmental impact of their use as spurred a revival in research into clean renewable alternatives. One promising area is solar thermal power produced at concentrating solar power (CSP) plants. Often the solar field at a CSP plant can absorb more energy than is required for baseline electricity generation, however, without a means of energy storage, it is difficult for these plants to match changes in demand and produce power when there is no sun. Therefore integrating thermal energy storage (TES) into CSP plants allows for a reduction in the levelized cost of electricity making solar power cost competitive with the current fossil fuel-based power plants. Currently, the majority of TES implemented at CSP plants around the world are molten salt sensible heat storage systems [1,2]. These systems require a large volume of storage material as well as insulated storage tanks to minimize heat loss. By utilizing a latent heat or thermochemical energy storage system the volume of storage material required to store the same amount of energy is immensely reduced.

While the energy efficiency of a TES system is an important factor in its performance and the overall system cost, the exergy efficiency of the system should also be considered as the purpose of the system is to store useful work and not simply energy [3]. The first law analysis of a system does not reflect the quality of the energy that is stored thus the second law analysis is required [4]. Exergy is the maximum useful work that can be produced by a system as it comes to equilibrium with the surroundings. Since the exergy efficiency (the ratio of exergy output to exergy input) of a system accounts for internal irreversibility, it is often lower when compared to the energy efficiency of the system [5–12].

Numerous numerical and experimental studies have been conducted into both researching novel materials to be used as PCMs [1,2,13–19] and into numerically evaluating the heat transfer that occurs within encapsulated phase change material (EPCM) capsules [20–25]. Only a few studies have investigated the exergetic efficiency of latent heat based TES systems [26,27] and none have focused on an EPCM based system. El-Dessouky and Al-Juwayhel [28] studied the effect of the inlet temperature of the HTF on the exergetic efficiency and showed that a maximum occurs when the smallest possible temperature difference is used between the initial PCM temperature and the inlet of the system during charging. Ramayya and Ramesh [6] studied the effect of sensible heating and sub-cooling on the performance of a shell and tube-based latent heat system and their results showed that sensible heating improves the efficiency of the melting process. Additionally, they found that the optimal melting temperature is

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Abbreviations: CSP, concentrating solar power; EPCMs, encapsulated phase change materials; HTF, heat transfer fluid; PCMs, phase change materials; TES, thermal energy storage.

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Nomenclature

G	Gravitational acceleration [m/s^2]
k	Turbulent kinetic energy [J/kg]
H	Total enthalpy [J/kg]
h_s	Sensible enthalpy [J/kg]
h_{sref}	Reference enthalpy [J/kg]
L	Latent heat of fusion [kJ/kg]
$\dot{m}$	Mass flow rate [kg/s]
p	Pressure [N/m^2]
r	Radius [m]
t	Time [s]
T_m	Melting temperature [K]
T_{ref}	Reference temperature [K]
u	Velocity component [m/s]
x	X coordinate [m]
y	Y coordinate [m]
c_p	Specific heat [J/kg K]
Re	Reynolds number [–]
Ste	Stefan number [–]
Fo	Fourier number [–]

Greek symbols

α	Volume fraction [–]
β	Thermal expansion coefficient [1/K]
γ	Liquid fraction [–]
τ_{ij}	Reynold's stresses [N/m^2]
μ	Dynamic viscosity [Pa s]
ν	Kinematic viscosity [m^2/s]
ρ	Density [kg/m^3]
ω	Specific dissipation rate [1/s]
κ	Thermal conductivity [W/m^2 K]
μ_t	Turbulent viscosity [Pa s]

Subscripts

i	Component
j	Component

higher for systems that include sensible heating and sub-cooling and that increasing the inlet HTF temperature during discharging increases the efficiency. Recently, Singh et al. [29] reported the effect of varying inlet temperatures in the exergy performance of NaCl impregnated graphite foam where they saw a similar trend and concluded that the optimal inlet temperature was 880 °C. In addition to the inlet temperature, the flow rate of the HTF is an important factor in the performance of a latent heat-based TES system. Although an increase in the flow rate increases the required pumping power and the resulting pressure drop across the system both leading to higher entropy generation and lower efficiency Erek and Dincer [11] showed the opposite to be true possibly due to the smaller temperature drop that is seen in the HTF as it residence time decreases. It should be noted that their analysis neglected the pumping power required during the exergy analysis.

It has often been shown in the literature that using a cascaded multiple-PCM system improves the energetic efficiency of latent heat based systems [30–34], however, limited studies have considered the exergetic efficiency of these systems [35–39]. As the temperature of the HTF decreases in the streamwise direction in a single-PCM system, multi-PCM systems utilizing PCMs with decreasing melting temperatures have better performance. Watanabe and Kanzawa [35] showed that the rapid charging and discharging seen in multi-PCM systems leads to high charging, discharging, and overall exergy efficiencies. Domanski and Fellah [38] reported a 40% increase in overall efficiency for a two-PCM system over that of a single-PCM system. Gong and Mujumdar [39] reported similar results that showed a 74% increase for a three-PCM system due to the decrease in the charging and discharging time of the system. Li et al. [40] studied the use of a two-PCM system for TES using finite-time thermodynamics and showed that an increase of 19–54% in efficiency is possible over that of a single-PCM system. Shabgard et al. [41] examined a cascaded latent heat storage system with gravity-assisted heat pipes and reported that the cascaded system recovered 10% more exergy over a 24-h cycle compared to the best non-cascaded system considered. Recently, Mosaffa et al. [42] reported on the energy and exergy performance of a multi-PCM system for free cooling applications. Their study showed that higher exergy efficiency was achieved when using multiple PCMs and that decreasing the temperature difference between the HTF and PCM yielded an increase in efficiency with time.

While these initial studies are a starting point, there are no reported studies on the exergy performance of EPCM-based latent heat TES systems for high-temperature applications. Therefore a numerical investigation was conducted for an example EPCM-based system to determine if the trend of an increase in performance would be seen for these systems as well. Based on the results of this investigation a greater understanding of the key factors in the behavior of large-scale TES systems will be gained. Present results can be used to further optimize high-temperature TES modules to improve the performance of CSP plants.

2. Mathematical modeling and numerical solutions

A 2-D numerical analysis was conducted to investigate the increase in the energy and exergy efficiency of an EPCM-based latent heat TES system by employing multiple PCMs. Six systems were considered: three single PCM systems ($NaNO_3$, $NaNO_2$, and KNO_3), a 2-PCM system ($NaNO_3$ and $NaNO_2$), a 3-PCM system, and a sensible heat only system as a comparison. The thermal properties used are listed in Table 1. Each system consisted of 72 cylindrical EPCM stainless steel capsules that had a diameter of 76.2 mm with a shell thickness of 1.5875 mm. A staggered arrangement of the capsules used to minimize the wake regions behind each capsules

Table 1
Properties of $NaNO_3$, $NaNO_2$, KNO_3, air, and stainless steel used in exergy simulations.

	$NaNO_3$	$NaNO_2$	KNO_3	Air	Stainless Steel
Melting Temperature (K)	581 [43]	555 [44]	610 [44]	–	1672 [45]
Density (kg/m^3)	1900 [43]	1812 [44]	1870 [44]	0.5214 [45]	7900[45]
Viscosity (Ns/m^2)	0.00285 [43]	0.002666 [44]	0.002367 [44]	3.65×10^{-5} [45]	–
Thermal Conductivity (W/mK)	0.550/0.680 [46]	0.665/0.765 [44]	0.481/0.878 [44]	0.0242 [45]	14.7[45]
Solid Heat Capacity(kJ/kg K)	1.588 [19]	1.733 [44]	1.240 [44]	–	477 [45]
Liquid Heat Capacity(kJ/kg K)	1.650 [19]	2.553 [44]	1.341 [44]	–	–
Gas Heat Capacity(kJ/kg K)	–	–	–	1.0064 [45]	–
Latent Heat (kJ/kg)	162.5 [19]	180.12 [44]	99.73 [44]	–	–